

# DAWN STATISTICAL MANEUVER DESIGN FOR VESTA OPERATIONS

Daniel W. Parcher<sup>\*</sup> and Gregory J. Whiffen<sup>†</sup>

In July of 2011 the Dawn spacecraft is scheduled to begin orbital operations at Vesta, a large main-belt asteroid. Dawn is a NASA Discovery mission that uses solar-electric low-thrust ion propulsion for both interplanetary cruise and orbital operations. Navigating between the Dawn project's four targeted science orbits at Vesta requires a plan that accounts for uncertainties not only in thrust execution, orbit determination, and other spacecraft forces, but also large uncertainties in characteristics of Vesta – such as the asteroid's gravity field and pole orientation. Accommodating these uncertainties requires strategic use of low-thrust maneuvers reserved for statistical trajectory corrections. This paper describes the placement and evaluation of low-thrust statistical maneuvers during two key phases of the Vesta mission along with a discussion of the tools, constraints, and methods used to plan those maneuvers.

## INTRODUCTION

In July of 2011 the Dawn spacecraft is scheduled to begin orbital operations at its first target -- Vesta, the 2<sup>nd</sup> most massive main-belt asteroid. Dawn is a NASA Discovery mission that uses solar-electric low-thrust ion propulsion for both interplanetary cruise and orbital operations. During its mission, the Dawn spacecraft will orbit both Vesta and Ceres. The planned observations of Vesta and Ceres are designed to provide insight into the conditions and processes acting during the formation of the solar system<sup>1</sup>.

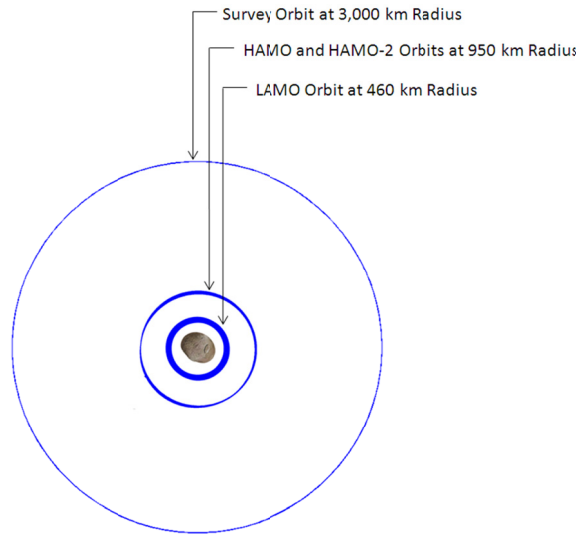
Four near-polar mapping orbits are planned for Vesta operations (see Figure 1). These four mapping orbits provide an opportunity to perform spectral analysis and visual and topographic mapping of Vesta's surface<sup>2</sup>. More detailed descriptions of the Dawn spacecraft's science instruments and science objectives at Vesta have been presented in other publications<sup>1,2,3,4,5</sup>. The first, and highest, targeted orbit at Vesta is Survey at 3000 km radius from Vesta. Survey provides the opportunity to perform low-resolution spectral analysis. The second mapping orbit is the High Altitude Mapping Orbit (HAMO) at 950 km radius. HAMO will be used primarily to perform visual and topographic mapping. The third and lowest mapping orbit is the Low Altitude Mapping Orbit (LAMO) at 460 km radius. The low LAMO altitude enables additional higher-resolution spectral analysis and gravity field determination. The final mapping orbit is the High

---

<sup>\*</sup> Member of the Engineering Staff, Guidance Navigation and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 264-820, 4800 Oak Grove Drive, Pasadena, California 91109-8099. E-mail: [Daniel.W.Parcher@jpl.nasa.gov](mailto:Daniel.W.Parcher@jpl.nasa.gov). Phone (818) 393-0457.

<sup>†</sup> Senior member of the Engineering Staff, Guidance Navigation and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 264-850, 4800 Oak Grove Drive, Pasadena, California 91109-8099.

Altitude Mapping Orbit 2 (HAMO-2), which has the same altitude as HAMO, but offers improved lighting conditions at northern latitudes due to its later timing at Vesta.



**Figure 1 - Vesta Science Orbits**

Navigating the transfers between these science orbits requires a plan that accounts for uncertainties not only in thrust execution, orbit determination, and other spacecraft forces, but also large uncertainties in characteristics of Vesta – such as the asteroid’s gravity field and pole orientation. Accommodating these uncertainties requires strategic use of low-thrust maneuvers reserved for statistical trajectory corrections.

This paper describes the placement and evaluation of low-thrust statistical maneuvers during two key phases of the Vesta mission: Approach to Survey, and the HAMO to LAMO Orbit Transfer. The maneuver design and statistical maneuver allocation for each of these phases are presented, along with a discussion of the relevant mission constraints for each phase.

## PROCESS

To support this analysis, the second author developed a software suite called Veil, a Monte Carlo trajectory optimization wrapper around the Static Dynamic Optimal Control Algorithm, embodied in a software toolset called Mystic<sup>6,7,8</sup>. Veil was used to re-optimize low-thrust trajectories to the science orbit targets while simulating errors in orbit determination, low-thrust maneuver execution, attitude control thrusting, as well as parameters of Vesta, including pole orientation, gravitational parameter, gravity harmonics, Vesta attitude at epoch, and Vesta rotational rate. Each of these parameters can be simulated by a variety of error models. Veil simulates both knowledge and truth values for each of these parameters, propagates control errors using truth samples, and designs future thrusting based on knowledge sampling of propagated truth values. The following section includes a description of Veil and how it was used to support the Dawn statistical maneuver allocation effort.

For this study, uncertainties and correlations for Vesta characteristics and spacecraft state knowledge were determined via orbit determination analysis of simulated radiometric tracking data and optical navigation images. Uncertainties for attitude control thrusting\* and maneuver execution errors were determined via analysis of spacecraft attitude control and orbit determination reconstruction of cruise. The techniques used to determine these uncertainties are not presented here, but a description of the assumed size of each of the uncertainties is included.

For this analysis, the Dawn spacecraft performance characteristics (thrust, mass-flow, and power) included in Reference 9 were used. See Reference 10 for additional discussion of Dawn spacecraft characteristics.

## VEIL

Orbit transfers at Vesta are accomplished via multiple open loop control periods (thrust sequences), each providing an opportunity to correct for errors accumulated during the previous period. For this study, Veil simulates execution of each of these open loop control periods. Each control period is executed while the next is being designed. The maximum size of each open loop control period is limited to a duration that can be flown successfully given the many sources of uncertainty outlined above. Modes of instability in some design processes become apparent only when all control periods are modeled as a fully daisy-chained design. The Veil toolset is designed to model the type of daisy-chain design process that will be used for the low-thrust transfers at Vesta.

Initially each transfer will be designed as a single end to end transfer or reference trajectory (all open loop design segments are designed simultaneously). The execution of the transfer will allow corrections to the reference trajectory to be designed for each open loop control period shortly before each period begins. The reference trajectory assumes the current knowledge of all necessary parameters at an epoch some time before the transfer begins. For example, the HAMO to LAMO reference trajectory is built during the HAMO science orbit. The reference trajectory includes time intervals that are reserved for future statistical thrusting. These time intervals come in two varieties – Maneuver Expansion Periods (MEPs) and Trajectory Correction Maneuvers (TCMs). MEPs allow thrusting periods in the reference trajectory to expand to account for uncertainties. TCMs are isolated periods where thrusting can be added to the reference trajectory to correct for statistical errors.

Veil requires a reference trajectory with a MEP and TCM plan in place as input. A partitioning of the transfer into open loop control periods must also be provided. The first step of the Monte Carlo process is to sample a delivery (truth) covariance of initial states at the epoch when the last orbit determination data is obtained for the reference trajectory. This “truth” state is used in conjunction with sampled true gravity and execution errors to provide the basis for the true trajectory evolution for a specific Monte Carlo case. Separate knowledge covariances are input to Veil that approximate how well we can know the true state at each of the design epochs. Design epochs are the knowledge epochs assumed for each open loop design cycle during the transfer. Veil then proceeds sequentially through the transfer designing each open loop design period based on the sampled knowledge of the previous open loop design’s truth propagation. Each design uses fully nonlinear optimization and propagation. A sequential design of all open loop periods during the

---

\* “Attitude control thrusting” refers to modeling of net thrust incurred from reaction wheel assembly momentum desaturation maneuvers performed by the reaction control thrusters.

transfer and the resulting true delivery to the target science orbit constitutes a single Monte Carlo “sample”.

## TRUTH ERROR MODELS

The Vesta gravity field model used for this analysis was developed by Alex Konopliv at the Jet Propulsion Laboratory. The field is an 8x8 uniform-density model of Vesta based on a Vesta shape model<sup>11</sup> and gravitational parameter of  $17.8 \text{ km}^3/\text{s}^2$ . Reference trajectories for both the Approach-to-Survey and HAMO to LAMO transfers were based on this uniform-density gravity field, and truth values for Veil simulations of both transfers were sampled from the uncertainties listed in Table 1 about this reference gravity field. For the Veil simulations presented here, the maneuver execution error models are composed of the maneuver magnitude and pointing uncertainties listed in Table 1. Maneuver execution errors assume a normal distribution\*. Maneuver execution errors are sampled at a frequency of once every 12 hours and applied uniformly to all thrust vectors during the sample time period. Thrust pointing errors are held fixed in the spacecraft frame between sample times. No time correlation between subsequent maneuver execution error samples was assumed.

**Table 1 - Uncertainties for Veil Simulation Truth Sampling**

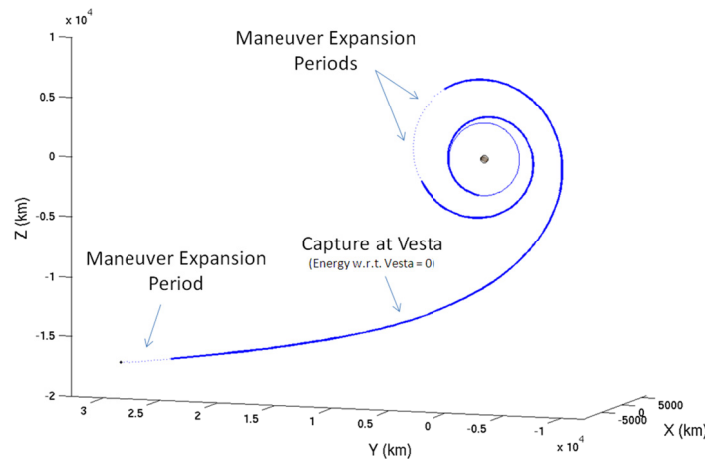
<b>Parameter</b>	<b>Approach to Survey Uncertainty<sup>†</sup> (Normal Distribution)</b>	<b>HAMO to LAMO Uncertainty<sup>†</sup> (Normal Distribution)</b>
Vesta GM ( $\text{km}^3/\text{s}^2$ )	$\mu=17.8, \sigma=0.41$	$\mu=17.8, \sigma=0.00022$
Vesta Pole (deg)	$\sigma=4.0$	$\sigma=0.0009$
Vesta J2	$\mu=0.0407, \sigma=100\%$	$\mu=0.0407, \sigma=0.01\%$
Vesta Harmonics	100%	4 <sup>th</sup> order: 1%, 5 <sup>th</sup> order: 33% 6 <sup>th</sup> order: 111%
Maneuver Magnitude**	0.5%	0.5%
Maneuver Pointing** (deg)	0.5	0.5
Attitude Control Thrust Magnitude*** (mm/s)	3	3
<sup>†</sup> Sampled with respect to design values. For Gravity, design values correspond to the uniform-density gravity field. ** Maneuver errors sampled and uniformly applied to thrust profiles every 24 hours early and every 12 hours late during Approach to Survey and every 12 hours during HAMO to LAMO. *** Attitude control thrust magnitude errors are applied every 12 hours in random directions.		

\* The Dawn spacecraft team continues to develop their understanding of maneuver execution error, especially the dependency on thrust vector rates and accelerations throughout designed thrust sequences. After the analysis presented here was completed, improved understanding of maneuver execution errors resulted in much more complex maneuver error modeling and has the potential to result in changes to the mission architecture.

## APPROACH TO SURVEY

Approach to Survey is the first “transfer” to a Vesta science orbit. Approach to Survey is the 97 day transition between interplanetary cruise and Vesta Survey orbit<sup>9</sup>. During cruise operations, cruise and approach thrusting are designed together as a minimum-time trajectory, getting to Vesta as fast as possible with thrusting planned at every opportunity. Design variations<sup>\*</sup>, statistical errors<sup>†</sup>, scheduling changes<sup>‡</sup>, or unplanned thrusting outages must therefore all result in variations in Survey arrival time. Such variations are accommodated by lengthening or shortening the duration of interplanetary cruise. However, to facilitate planning for navigation, science, and spacecraft operations, this variability in Survey arrival date is permitted only during cruise operations, and not during Approach. The Approach to Survey trajectory therefore begins as a fixed 97 day trajectory with thrusting at every available opportunity.

Since statistical errors will continue to perturb the spacecraft trajectory during Approach operations, additional control authority is needed to ensure delivery to Survey orbit in the time available. This additional control authority is allocated in the form of MEPs throughout Approach. Each MEP is a block of coasting set aside for statistical thrusting to correct for perturbations to the spacecraft trajectory and to account for knowledge of Vesta’s physical parameters as they become better known. When designing a thrust sequence for execution, MEPs within that sequence (and only within that sequence) are made available for additional thrusting. The 97-day Approach to Survey trajectory contains 10 MEPs, for a total of 7.5 days in duration. The final 27 days of Approach to Survey are shown in Figure 2.



**Figure 2 - Trajectory Plot of the Final 27 days of Approach-to-Survey Reference Transfer about a Uniform-Density Vesta (Bold Indicates Thrusting)**

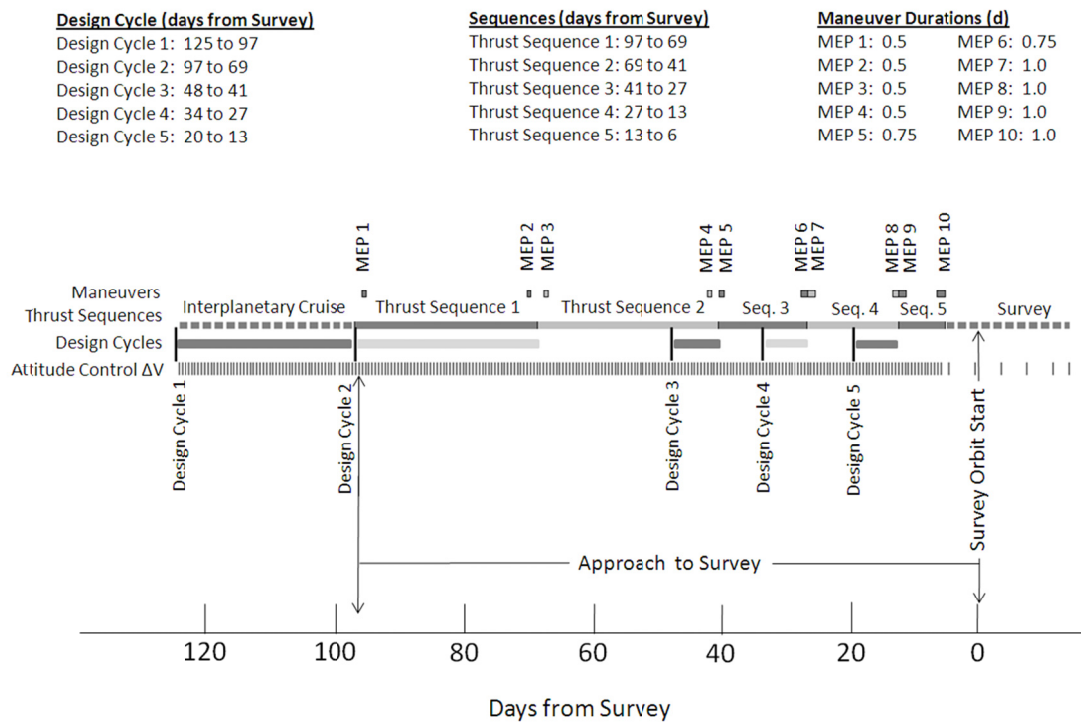
\* Design variations include the addition of trajectory constraints or targets, modifications to the target orbit, or changes in spacecraft performance models such as solar array power, thrust capability, propellant consumption, attitude control thrusting, spacecraft system power consumption, or spacecraft mass.

† Statistical error sources include orbit determination estimation uncertainties, maneuver execution error, and changes in Vesta physical characteristics such as Vesta orientation or gravity field.

‡ Scheduling changes include changes to spacecraft activity durations, radiometric tracking, optical navigation, or science observation schedules.

During interplanetary cruise, thrusting sequences are loaded to the spacecraft on a 5-week schedule<sup>12</sup>. Every 5 weeks, thrust vectors from the start of the sequence all the way to Survey orbit are re-optimized to a new Survey orbit entry date based on the minimum-time trajectory. The new thrust vectors account for design variations, statistical errors, and scheduling changes referred to earlier. In 5 weeks, errors during interplanetary cruise typically propagate to over 5,000 km of position and 2 m/s in velocity at the start of the next sequence. One of the key ways to reduce this error is to increase the frequency with which the thrust vectors are updated to correct for observed errors. The frequency with which thrusting sequences can be designed is limited by tracking schedule availability and ground personnel support. The process of performing the final estimation of the spacecraft state, and performing the final estimation of Vesta's characteristics, as well as designing, sequencing, and uploading a given thrusting sequence is referred to as a "design cycle". Design cycles vary in length throughout Approach, but are generally as long as possible to provide ample time for development while being short enough to deliver the spacecraft to its target accurately.

After performing many Veil analyses on alternate approach plans, it was determined that Approach should contain 5 thrust sequences (see Figure 3). Each thrust sequence is equal to or shorter in duration than the previous thrust sequence. These sequences transition from a near-cruise duration of 28 days to a one-week sequence just before Survey. The design cycle durations correspondingly shrink from 28 days to only one week for the final three thrust sequences. As the spacecraft enters Vesta's gravity field, errors propagate more dramatically, requiring shorter thrust sequences and shorter design cycles in which to build them. Capture at Vesta (shown in Figure 2) occurs during Thrust Sequence 4. The final 1.5 revolutions of the transfer occur during Thrust Sequence 5.



**Figure 3 - Approach to Survey Thrust Sequence, Design Cycle, and Maneuver Expansion Period Timeline**

As is the case during interplanetary cruise, each Approach to Survey thrust sequence is designed to retarget Survey orbit, with changes not only to the thrust sequence being designed, but to all future thrust vectors leading up to Survey orbit. The Veil Monte Carlo simulation of Approach to Survey simulates this behavior as well, targeting Survey orbit with each thrust sequence design, but only executing the next thrust period before re-optimizing again.

Table 2 shows orbit determination uncertainties at the start of the design cycles. A substantial improvement in Vesta's pole estimation is obtained between design cycles 3 and 4 due to rotational characterization images taken between these designs. Knowledge in Vesta's gravitational parameter is also substantially improved by design cycles 4 and 5, after capture at Vesta is achieved\* and Vesta's gravity begins to show a strong signal in spacecraft radiometric tracking data. Early knowledge of Vesta's pole and gravitational parameter is key to successfully targeting Survey. Statistical thrusting durations required to correct for these errors increase dramatically the later the knowledge is obtained. The knowledge of J2 is not expected to improve significantly during Approach. Only after thrusting ends and Survey starts will measurements improve J2 estimation.

**Table 2 - Orbit Determination 1 $\sigma$  Knowledge at Design Epochs for Veil Simulation of Approach to Survey**

<b>Orbit Determination Knowledge Time</b>	<b>Position (km)</b>	<b>Velocity (m/s)</b>	<b>GM (km<sup>3</sup>/s<sup>2</sup>)</b>	<b>Pole (deg)</b>	<b>Rotation (deg/day)</b>	<b>J2 (normalized)</b>
Injection	548	0.626	0.407	3.886	0.00029	0.0200
Design Cycle 1 Start	2,320	0.992	0.407	3.886	0.00029	0.0200
Design Cycle 2 Start	1,495	0.766	0.407	3.886	0.00029	0.0200
Design Cycle 3 Start	188.7	0.302	0.407	3.886	0.00029	0.0200
Design Cycle 4 Start	180.4	0.350	0.314	0.618	0.00021	0.0200
Design Cycle 5 Start	169.7	1.880	0.025	0.247	0.00001	0.0200

During the first three thrusting sequences of Approach, knowledge of Vesta's gravitational parameter and pole does not improve (see Table 2). Sampling the knowledge in Vesta's pole or GM for these first three sequences during a Veil simulation therefore would lead to variations in the knowledge estimate of GM and pole that would not occur during operations. The estimation of the pole and GM will not change during operations if there is no new data upon which to base a new estimation. Since sampling Vesta's pole and GM during this time is not an accurate representation of what will occur during operations, and results in large changes to the sampled values (thereby artificially forcing significant thrust vector corrections), the pole and GM knowledge are not sampled until the fourth design cycle. Note that the truth pole and GM are always sampled once at the start of each Veil Monte Carlo simulation.

The Veil Monte Carlo analysis of Approach was performed based on the Approach architecture shown in Figure 3, the orbit determination uncertainties indicated in Table 2, and the maneuver execution models in Table 1. A total of 2,231 full simulations of Approach were completed.

---

\* Vesta capture indicates zero spacecraft orbital energy with respect to Vesta.

Each Approach simulation consisted of 5 thrust sequence designs including a redesign of all thrusting between the thrust sequence epoch and Survey arrival.

Table 3 indicates the feasibility of each of the simulations listed by thrust sequence. For Approach, feasibility is measured as the ability to design a trajectory that reaches the Survey target to within tolerances given the total thrusting time available (including MEPs and TCMs) for a given thrust sequence and current knowledge. A successful Survey delivery achieves the following target and tolerances: (1) an orthogonal Vesta relative velocity and position (within 4 arc minutes); (2) a circular orbit velocity (within 5 cm/s); (3) the desired orbit normal (within 4 arc minutes); and (4) the desired orbital period (within 3 minutes). The targeting of Survey is phase free. The above tolerances must be met without violating the thrust magnitude constraint.

It is important to note that as knowledge of Vesta physical parameters improve, the targets defined above will change. Large changes in knowledge (for example pole orientation and gravitational parameter) can place a great deal of strain on the limited control authority available and cause failures in feasibility in sequences 3, 4, and 5. However, this level of feasibility is considered acceptable for navigation. It is interesting to note that the feasibility in Sequence 5 is larger than Sequence 4, indicating that some design failures in Sequence 4 were able to recover once MEPs in Sequence 5 became available.

**Table 3 - Approach to Survey Veil Simulation Design Feasibility**

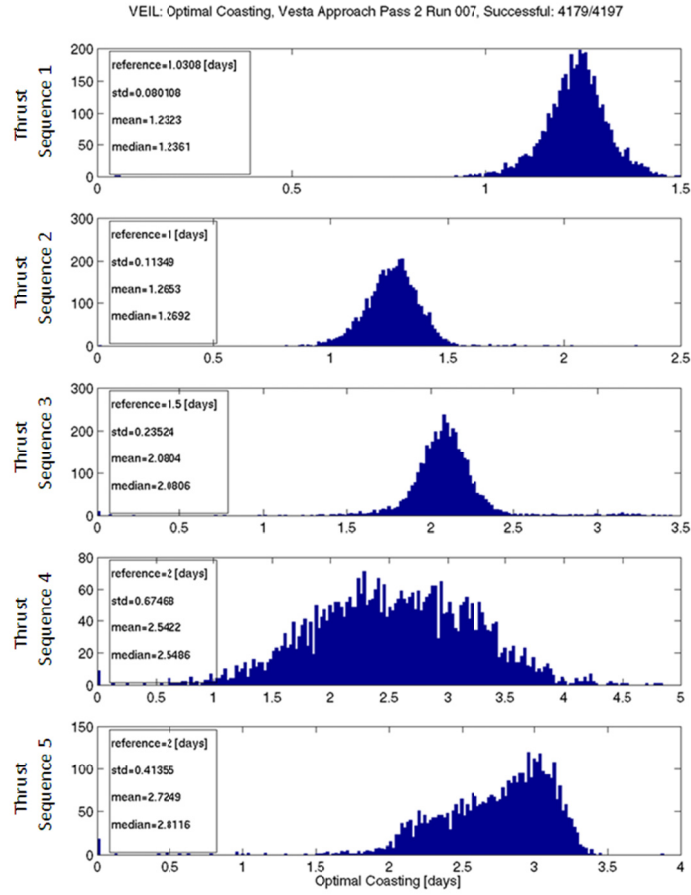
Thrust Sequence Design	Feasibility
Sequence 1	100%
Sequence 2	100%
Sequence 3	99.86%
Sequence 4	99.55%
Sequence 5	99.59%

Figure 4 shows optimal coasting\* during the designs. Feasibility failures have zero optimal coasting. Interestingly, as shown in Figure 4, many of the thrust sequences have an average optimal coasting duration greater than the duration of the MEPs. This indicates that, once available for thrusting, the MEPs occur at more efficient times than other portions of the thrust sequence, thereby allowing a longer overall coasting duration. Optimal coasting typically resides toward the middle of the thrust sequence, as the optimizer prefers to use the leverage available by placing thrust at the beginning and end of the thrust sequence. This behavior was discovered during early Veil analysis of Approach, and indicated that, to ensure that MEPs were placed at the most effective location during each thrust sequence, MEPs should be placed at the beginnings and ends of each thrust sequence.

---

\* Optimal coasting is coasting that occurs when additional thrusting is not needed to achieve the desired target in the flight time allowed.



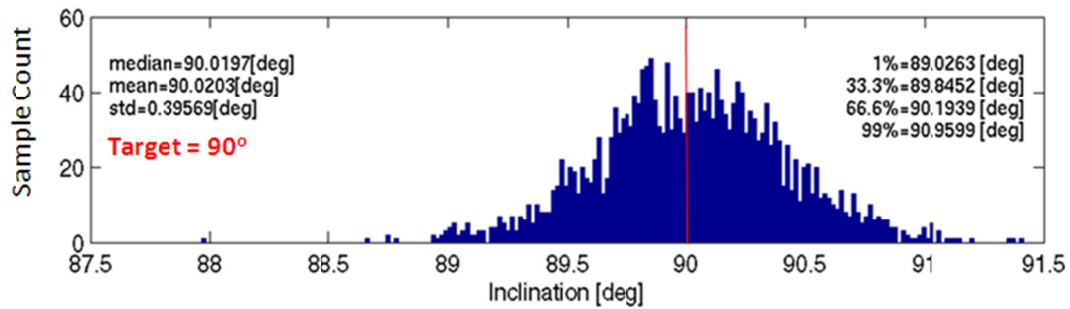


**Figure 4 - Approach to Survey Veil Simulation Optimal Coasting by Thrust Sequence**

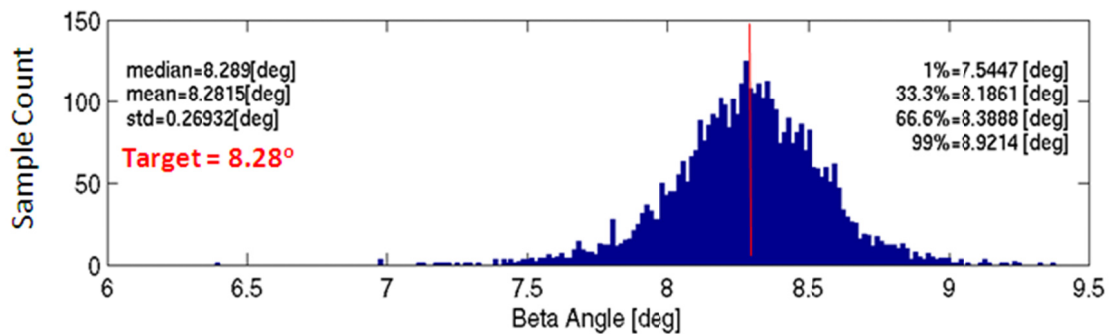
Figure 5, Figure 6, and Figure 7 show Veil simulation delivery accuracy to Survey in inclination,  $\beta$  angle, and orbital period, respectively. The  $\beta$  angle is the angle between the orbit plane and the Vesta-Sun line<sup>9</sup>. The dispersions for inclination and  $\beta$  angle are well within the Survey orbit delivery tolerances of  $10^\circ$ , and  $5^\circ$  respectively. The primary concern for delivery is orbital period, shown in Figure 7. The Survey science plan depends heavily on orbital period, and is built to accommodate a 45 minute variation in orbital period about the target of 68 hours. The Veil results include many samples that deliver to significantly longer orbital periods. While orbital periods that are too long can still contain the science sequences, they require late changes to the science sequence. There is currently no plan to redesign Approach to improve the Survey orbit period delivery.

The initial phase in Survey orbit is not a targeted parameter during the Veil simulation, and will not be targeted during actual Approach operations. Early plans for Approach included targeting initial Survey orbit phase, but this restriction requires the time set aside for MEPS to be considerably longer. Dropping the initial phase as a target resulted in a reduction of MEP sizes, which translated to an earlier Survey arrival date, and a greater time available at Vesta overall. However, phase-free Survey targeting adds complexity to observations of Vesta that are sensitive to phase angle during Approach, such as optical navigation images, rotational characterization images, and science instrument calibrations. These observations may require additional tolerance

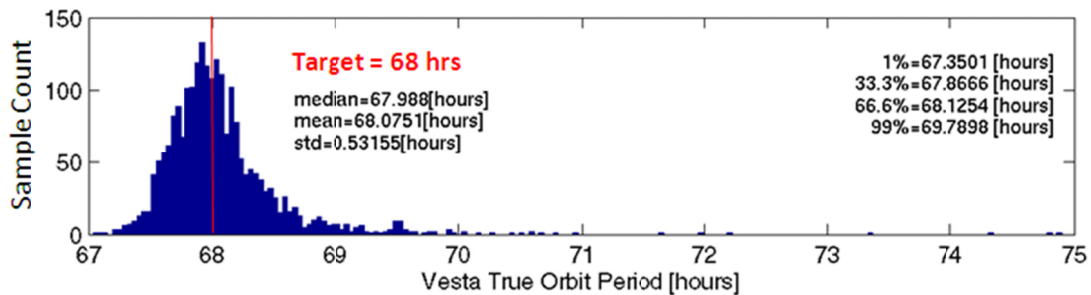
to variation in Vesta phase angle or may require last-minute updates to event timing or pointing to accommodate design changes.



**Figure 5 - Achieved Survey Inclination for all Approach Veil Samples**



**Figure 6 - Achieved Survey Beta Angle for all Approach Veil Samples**

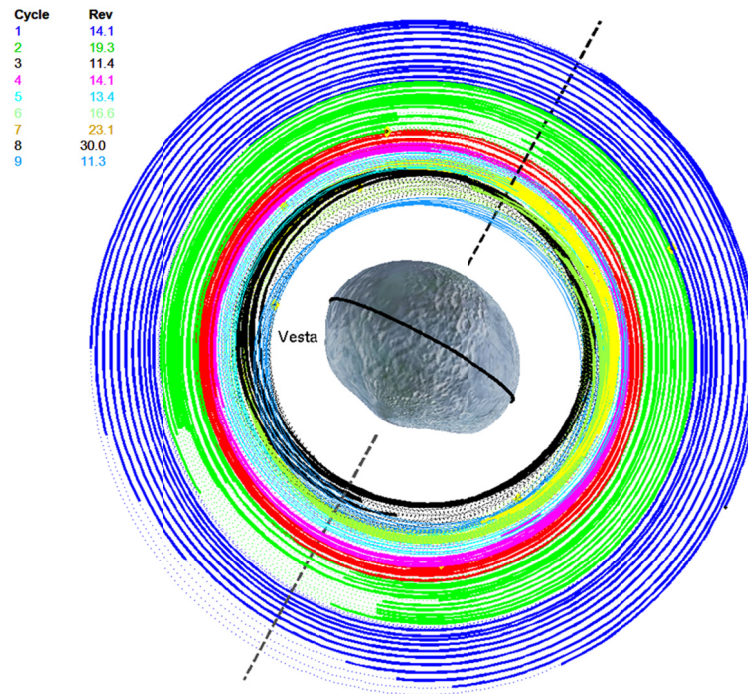


**Figure 7 – Achieved Orbital Period for All Approach Veil Samples**

## HIGH ALTITUDE MAPPING ORBIT TO LOW ALTITUDE MAPPING ORBIT

The HAMO to LAMO transfer statistical simulation differs greatly from Approach to Survey. During Approach to Survey, Vesta's physical characteristics are not well known. Survey is a stable orbit, and delivery tolerances are generous. During the HAMO to LAMO transfer, Vesta's physical characteristics will be significantly better understood, but sensitivities to maneuver exe-

cution errors, orbit determination knowledge, and attitude control thrusting errors cause state divergence quickly in the presence of Vesta's dynamic gravity field. After using Veil to test many alternative architectures for the HAMO to LAMO transfer, it was determined that this transfer can be completed with 9 thrust sequences. The HAMO to LAMO transfer spans over 170 revolutions around Vesta as it reduces the spacecraft's orbital radius from 950 to 460 km. Figure 8 illustrates the transfer, indicating each of the thrust sequences. References 9, 13 and 14 include a more detailed description of the HAMO to LAMO trajectory and the HAMO and LAMO orbits.

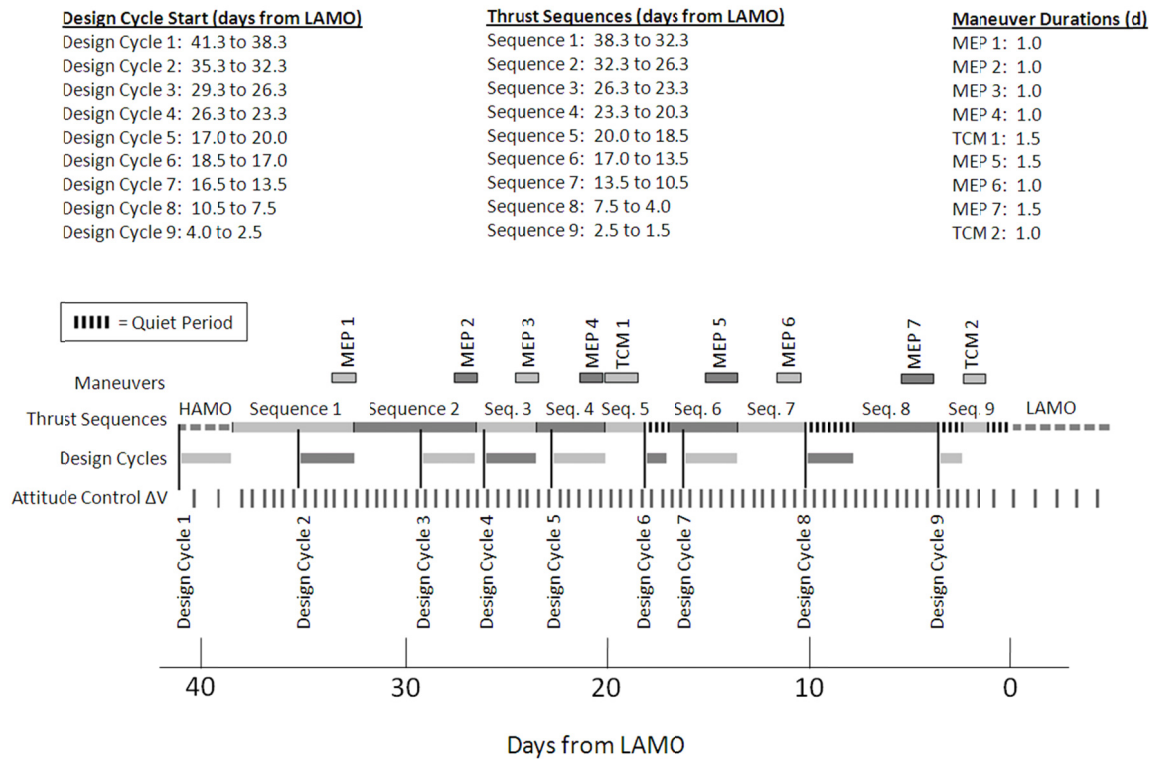


**Figure 8 - HAMO to LAMO Transfer Trajectory (Colors Represent Thrust Sequences)**

During Approach-to-Survey, the trajectory is redesigned to Survey for each thrust sequence. Unlike Approach-to-Survey, the Veil simulation of the HAMO to LAMO transfer utilizes waypoint targeting throughout. Waypoints are intermediate reference trajectory states (position and velocity) that each thrust sequence targets. Targeting to the reference trajectory waypoints enables thrust sequences to be designed independently, each design aiming to restore the reference trajectory characteristics for the remainder of the transfer and LAMO. Waypoint targeting was chosen because it is simple to implement and works reliably according to Veil analysis. The process of obtaining a new state estimate, developing new thrust vectors, and sequencing those thrust vectors is compounded by the complexity of the design. A single HAMO to LAMO reference trajectory requires more than a week to design (including stability analysis<sup>14</sup>). Accommodating a complete redesign to LAMO for each thrust sequence would significantly increase design cycle durations and cost months of flight time. Instead, each thrust sequence simply targets back to the corresponding waypoint along the reference trajectory at the end of the thrust sequence. This technique greatly reduces the complexity of each thrust sequence design, significantly reduces design time, and reduces impacts to observations or activities that are sensitive to Vesta phase.

The HAMO to LAMO transfer takes place over 38.3 days, including only 10.5 days of deterministic thrusting and 10.5 days of statistical thrusting in 9 thrust sequences. A schedule for the transfer is provided in Figure 9. A description of knowledge uncertainties at design epochs

throughout the transfer is included in Table 4. Each thrust sequence contains one statistical thrusting block at the end. Unlike the Approach-to-Survey transfer, where MEPs needed to be placed at the beginning and end of each thrust sequence, the short orbital period\* during the HAMO to LAMO transfer provides sufficient geometric change throughout the MEPs. In addition to MEPs, the HAMO to LAMO transfer also has two Trajectory Correction Maneuvers (TCMs), which are purely statistical thrust sequences, unlike thrust sequences containing MEPs which also contain deterministic thrusting. TCMs are used to provide higher-accuracy deliveries at key targets. In the case of the HAMO to LAMO transfer, TCM-2 (see Figure 9) is needed to support delivery to LAMO, while TCM-1 minimizes errors at the critical 1:1 resonance between Vesta’s rotational rate and the spacecraft orbital period. Orbits near the 1:1 resonance experience large gravitational perturbations which significantly exaggerate spacecraft state errors. Further discussion of the resonance can be found in References 9 and 15.



**Figure 9 - HAMO to LAMO Thrust Sequence, Design Cycle, and Maneuver Expansion Period Timeline**

In addition to MEPs and TCMs, the HAMO to LAMO transfer also utilizes three coasting blocks referred to as “Quiet Periods”, which provide ground personnel the opportunity to design a new thrust sequence while the spacecraft is not thrusting. Quiet periods are expensive in terms of flight time, but eliminate maneuver execution errors and reduce attitude control thrusting fre-

\* The orbital period during the HAMO to LAMO transfer starts at the 12 hour HAMO orbital period and ends at a 4 hour period in LAMO.

quency while the next thrusting sequence is designed. Quiet Periods are primarily needed at altitudes near or below the 1:1 resonance.

**Table 4 – HAMO to LAMO Veil Simulation Orbit Determination  $1\sigma$  Knowledge at Design Epochs**

<b>OD Knowledge Time</b>	<b>Position (km)</b>	<b>Velocity (m/s)</b>	<b>GM (km<sup>3</sup>/s<sup>2</sup>)</b>	<b>Pole (deg)</b>	<b>Rotation (deg/day)</b>	<b>J2 (normalized)</b>
Injection	15.978	2.205	0.000217	0.00092	1.7e-7	4.54e-6
Design Cycle 1 Start	1.5002	0.20792	0.000223	0.00054	1.7e	1.16e-6
Design Cycle 2 Start	7.4119	1.4492	0.000220	0.00053	1.7e	0.99e-6
Design Cycle 3 Start	6.2591	1.6608	0.000219	0.00053	1.7e	0.82e-6
Design Cycle 4 Start	6.2712	1.7717	0.000204	0.00053	1.7e	0.72e-6
Design Cycle 5 Start	14.7818	5.2791	0.000201	0.00053	1.7e	0.64e-6
Design Cycle 6 Start	0.47646	0.15221	0.000193	0.00053	1.7e	0.48e-6
Design Cycle 7 Start	4.9245	1.7004	0.000174	0.00053	1.7e	0.44e-6
Design Cycle 8 Start	0.65263	0.24929	0.000164	0.00053	1.7e	0.34e-6
Design Cycle 9 Start	0.011283	0.00548	0.000157	0.00048	1.7e	0.24e-6

All but two design cycles during the HAMO to LAMO transfer are 3 days in duration. The remaining two designs are only 36 hours in duration, associated with 36 hour quiet periods, designed to achieve as accurate a delivery as possible. The first 36 hour design occurs immediately following the 1:1 resonance (design cycle 6), and the second occurs near LAMO (design cycle 9), both areas where delivery accuracy is crucial. Table 5 shows delivery accuracies to the start of each thrust sequence throughout the transfer. For the resonance (see the start of sequence 6), delivery accuracy is critical to avoid deviating from the designed trajectory too far to recover using available MEPs. For LAMO, delivery accuracy is critical to avoid nearing Vesta occultation of the Sun, a spacecraft safety requirement<sup>13</sup>.

To help ensure that the HAMO to LAMO transfer is resilient to errors and perturbations, a powered-flight stability analysis was performed on the reference trajectory<sup>14</sup>. This stability analysis identified portions of the transfer that are particularly sensitive to perturbations during powered flight. The powered-flight stability analysis helped indicate where Quiet periods, TCMs, or shorter design cycles are necessary to improve waypoint delivery accuracy – primarily at and just below the 1:1 resonance.

The Veil Monte Carlo analysis of the HAMO to LAMO transfer was based on the transfer architecture shown in Figure 9, the orbit determination uncertainties indicated in Table 4, and the maneuver execution model in Table 1. The Veil results include 1,473 full simulations of the transfer, each consisting of 9 optimized thrust sequences individually targeted back to the reference trajectory waypoints based on sampled knowledge. Computation time for this analysis is about 1.3 full HAMO to LAMO simulations per CPU per day, or 1,134 CPU-days in total to obtain 1,473 complete designs.

**Table 5 – HAMO to LAMO Veil Simulation 1 $\sigma$  Delivery Accuracy to Thrust Sequence Start**

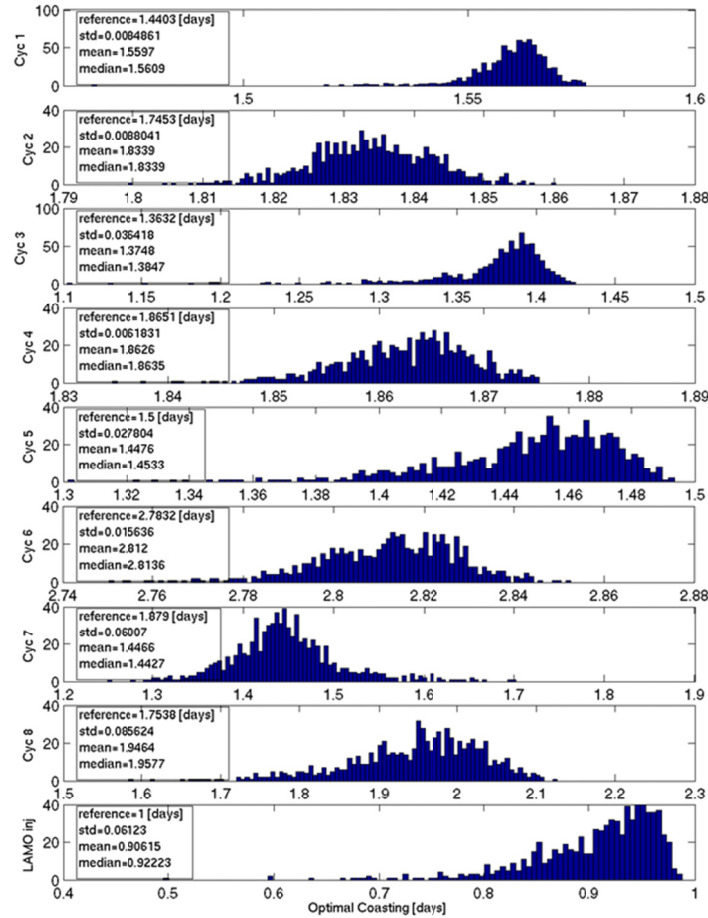
<b>Thrust Sequence Start</b>	<b>Position Error (km)</b>	<b>Velocity Error (m/s)</b>
Injection	15.98	2.205
Thrust Sequence 1	40.02	5.725
Thrust Sequence 2	13.02	2.549
Thrust Sequence 3	25.29	6.534
Thrust Sequence 4	10.01	2.836
Thrust Sequence 5	16.89	6.008
Thrust Sequence 6	9.86	3.138
Thrust Sequence 7	4.97	1.712
Thrust Sequence 8	12.45	4.754
Thrust Sequence 9	20.91	9.805
<b>LAMO</b>	<b>1.233</b>	<b>0.483</b>

A successful HAMO to LAMO transfer architecture requires both design feasibility and an accurate delivery to LAMO. All simulations returned a feasible design for all thrust sequences for the HAMO to LAMO transfer. In this case, feasibility is measured as the ability to design a trajectory for a given thrust sequence that successfully targets the corresponding reference trajectory waypoint, without violating the thrust magnitude constraint, and without missing the state target by more than 1 km and 9 cm/s.

There are two primary metrics for a successful LAMO delivery -- adequate LAMO ground-track coverage<sup>9</sup>, a criteria which is satisfied in all 1,473 Veil samples, and stable  $\beta$  angle at the beginning of LAMO until the first LAMO orbit maintenance maneuver (OMM). Satisfying the latter requirement relies primarily upon LAMO delivery accuracy (see Table 5), but is aided by targeting a LAMO that is selected specifically for  $\beta$  angle stability<sup>13</sup>. An OMM analysis conducted on candidate stable LAMOs established a 1 $\sigma$  LAMO delivery requirement of 2 km in position and 1 m/s in velocity to ensure controllability. This requirement is well satisfied by the 1.2 km, 0.5 m/s LAMO delivery achieved by the Veil simulations (see Table 5). Notably, this delivery accuracy could not be accomplished without the aid of TCM-2, the purely statistical thrust sequence prior to LAMO. TCM-2 is preceded by a short design cycle during a quiet period to ensure the best possible delivery. Without TCM-2, the delivery to LAMO would be 20.4 km and 9.6 m/s 1 $\sigma$ , resulting in unacceptable  $\beta$  angle drift during LAMO.

From an attitude control perspective, the HAMO to LAMO transfer contains some of the most aggressive thrust profiles anticipated at any time on the Dawn mission. The short orbital period coupled with significant out-of-plane thrusting results in thrust profiles that require significant rates and accelerations in spacecraft attitude. Higher attitude control rates and accelerations result in larger maneuver execution errors (both from spacecraft pointing and thruster gimbaling) and increased attitude control thrusting. Thrust vector directional rates and accelerations increase rapidly as optimal coasting in a given thrust sequence decreases. As a result, significant optimal

coasting during the HAMO to LAMO transfer helps reduce maneuver execution errors and further improves feasibility and delivery accuracy. Optimal coasting throughout the HAMO to LAMO transfer can be seen in Figure 10. The maneuver execution error model used for this analysis requires significant optimal coasting in each of the thrust sequences to maintain the validity of the model.



**Figure 10 – HAMO to LAMO Veil Simulation Optimal Coasting by Thrust Sequence**

## Quiet Periods

Early HAMO to LAMO transfer designs did not include quiet periods, and resulted in infeasibilities in sequences following the 1:1 resonance (sequences 6-9). In general, there are a number of methods used to improve feasibility for a given thrust sequence. First, one method is to increase the duration of MEPs during the thrust sequence. Alternatively, a second method to improve feasibility is to improve the delivery from the previous sequence. A third method is to lengthen the thrust sequence, offering a larger lever arm to thrust vector changes. Lengthening the thrust sequence to improve feasibility was never explored due to degradation of delivery to subsequent thrust sequences. Finally, a fourth method to improve design cycle feasibility is to redesign the reference trajectory to improve powered flight stability<sup>14</sup>, an option that is beyond the scope of this paper.



Regarding the first method, it is generally straightforward to determine the increase in MEP duration needed to improve feasibility, simply by observing the amount of additional thrusting required to enable the infeasible samples to reach the target. It is important to consider, however, that an increase in MEP size will generally increase delivery errors to the following thrust sequence\*. The size of the MEP required to achieve sufficient feasibility may also not be realistic for the flight time allowed. In the case of infeasibilities following the resonance, increasing the MEP size was not an attractive option due to the dynamic environment. An increase in MEP size corresponds to increased total maneuver execution error and an increase in thrust sequence delivery error.

The second viable option for reducing infeasibilities in sequences 6 through 9 was to improve the delivery error from the previous thrust sequence. Improving the previous sequence delivery error can be accomplished in a number of ways: improving the orbit determination knowledge at the design epoch for the previous sequence, shortening the design cycle for the previous sequence, requiring a Quiet Period during the design cycle of the previous sequence, or simply shortening the previous sequence to reduce maneuver execution errors. Each of these will result in improved delivery accuracy and an increase in design feasibility. For the HAMO to LAMO transfer, improving the orbit determination knowledge was not pursued because no clear correlation could be determined between poor orbit determination knowledge and infeasible cases. Delivery error was large despite excellent state knowledge at the start of the design. Shortening the design cycle was also not an option, as the three day design cycle was the minimum design cycle allowable for this time period with the ground resources available. Shortening the thrust sequence was also not a viable option given the design cycle schedule. The only option remaining was to implement a “Quiet Period”. Quiet periods are often a last resort due to the flight time they require. In this case, the presence of a quiet period improved feasibility from 92% to 100% of all samples.

## CONCLUSIONS

The Monte Carlo trajectory optimization tool called Veil was used to investigate trajectory sensitivities to statistical variation in spacecraft performance, orbit determination and key characteristics of Vesta. This analysis was used to design trajectory architectures that include statistical maneuvers capable of correcting for these error sources. Veil was then used to show that a high percentage of the perturbed trajectories are capable of delivering to the targeted science orbits to within required tolerances.

Orbit transfers were divided into thrust design cycles to minimize thrust-execution errors and to take advantage of increasing knowledge of Vesta, while maintaining a supportable sequence development schedule for the Dawn Flight Team. Each design cycle contained deterministic thrusting needed to achieve orbit targets, and maneuver expansion periods (MEP) or a trajectory correction maneuver (TCM) period reserved for statistical thrusting needed to correct errors.

For the Approach-to-Survey architecture presented, Veil was used to compute 2,231 Vesta-Approach-to-Survey trajectories, each of which included 5 design cycles individually targeted to

---

\* This holds true for feasible samples only. Infeasible samples will have large delivery errors. Increasing MEP size will generally improve feasibility for a given thrust sequence, which will improve delivery errors across all samples. However, when considering only feasible samples, the increased flight time will result in increased delivery error.



Survey orbit. Of the trajectories computed, 99.56% achieved Survey orbit conditions to the required tolerance.

For the HAMO to LAMO Orbit Transfer architecture presented, Veil was used to compute 1,473 trajectories, each of which included 9 design cycles individually targeted to pre-determined intermediate waypoints. Of the transfers computed, 100% achieved the LAMO orbit conditions to the required tolerance.

Achieving the necessary design feasibility throughout the transfers and delivery accuracy to the targeted science orbits required strategic placement of MEPs, purely statistical Trajectory Correction Maneuvers, Quiet Periods, and short design cycles. Placement was dictated by Vesta's dynamic gravity environment and science orbit tolerances. Accurate delivery to the Survey and LAMO science orbits will help ensure successful scientific observations of Vesta.

## ACKNOWLEDGEMENTS

The authors would like to thank Christopher Potts for his consultation during early Veil architecture development. The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Copyright 2011 California Institute of Technology. Government sponsorship acknowledged.

## REFERENCES

- <sup>1</sup> Russel C.T. *et al.*, "Dawn: A journey in space and time", *Planetary and Space Science*, Vol. 52, Issues 5-6, April-May 2004, pp. 465-489.
- <sup>2</sup> Rayman, M.D. *et al.*, "Dawn: A mission in development for exploration of main belt asteroids Vesta and Ceres", *Acta Astronautica*, Vol. 58, Issue 11, June 2006, pp. 605-616.
- <sup>3</sup> Rayman, M.D., and Keyur C. Patel, "The Dawn project's transition to mission operations: On its way to rendezvous with (4) Vesta and (1) Ceres", *Acta Astronautica*, Vol. 66, Issues 1-2, January-February 2010, pp. 230-238.
- <sup>4</sup> T.H. Prettyman, *et al.*, "Gamma ray and neutron spectrometer for the Dawn Mission to 1 Ceres and 4 Vesta", *IEEE Transactions on Nuclear Science*, Vol. 50, Issue 4, August 2003, pp. 1190-1197.
- <sup>5</sup> T.H. Prettyman, *et al.*, "Mapping the elemental composition of Ceres and Vesta: Dawn's gamma ray and neutron detector", *Proceedings of SPIE*, Vol. 5660, December 2004, pp. 107-116.
- <sup>6</sup> Whiffen G.J., "Static/Dynamic Control for Optimizing a Useful Objective," United States Patent No. 6,496,741, Issued Dec. 17, 2002, Filed Mar. 25, 1999.
- <sup>7</sup> Whiffen G.J., and Sims, J.A., "Application of SDC Optimal Control Algorithm to Low-Thrust Escape and Capture Including Fourth Body Effects," 2nd International Symposium on Low Thrust Trajectories, Toulouse, France, June 18-20, 2002
- <sup>8</sup> Whiffen G.J., "Mystic: Implementation of the Static Dynamic Optimal Control Algorithm for High-Fidelity, Low-Thrust Trajectory Design", Paper AIAA 2006-6741, AIAA/AAS Astrodynamics Specialist Conference, Keystone, Colorado, Aug. 21-24, 2006.
- <sup>9</sup> Parcher, D.W., "Low-Thrust Orbit Transfer Design for Dawn Operations at Vesta", Paper AAS 2011-183, AIAA/AAS Astrodynamics Specialist Conference, New Orleans, Louisiana, Feb. 13-17, 2011.
- <sup>10</sup> Rayman, M.D. *et al.*, "Coupling of system resource margins through the use of electric propulsion: Implications in preparing for the Dawn mission to Ceres and Vesta", *Acta Astronautica*, Vol. 60, Issue 10-11, May-June 2007, pp. 930-938.

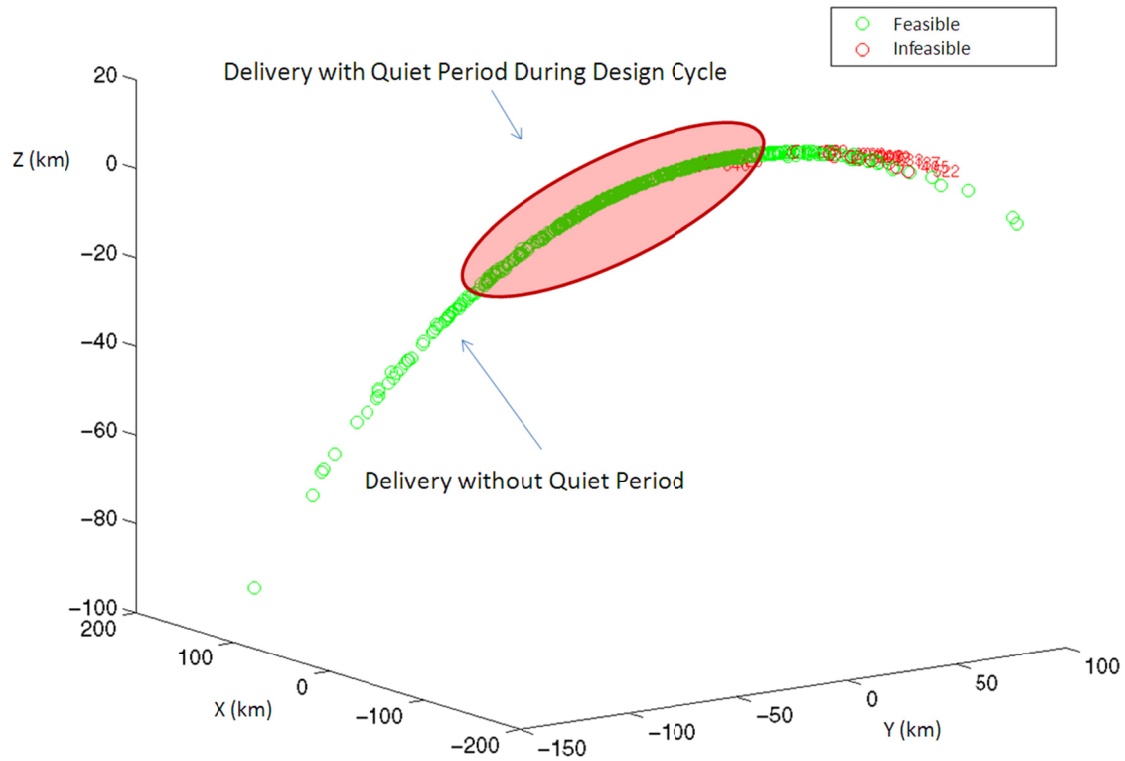
<sup>11</sup> Thomas P.C. *et al.*, "Impact Excavation on Asteroid 4 Vesta: Hubble Space Telescope Results", *Science*, Vol. 227, no. 5331, Sep. 5, 1997, pp. 1492-1495.

<sup>12</sup> Rayman, M.D., and Keyur C. Patel, "The Dawn project's transition to mission operations: On its way to rendezvous with (4) Vesta and (1) Ceres", *Acta Astronautica*, Vol. 66, Issues 1-2, January-February 2010, pp. 230-238.

<sup>13</sup> Whiffen G.J., "Low Altitude Mapping Orbit Design and Maintenance for the Dawn Discovery Mission at Vesta", Paper AAS 2011-182, AIAA/AAS Astrodynamics Specialist Conference, New Orleans, Louisiana, Feb. 13-17, 2011.

<sup>14</sup> Whiffen G.J., "The Stability of Powered Flight Around Asteroids With Application to Vesta", Paper AAS 2011-186, AIAA/AAS Astrodynamics Specialist Conference, New Orleans, Louisiana, Feb. 13-17 2011.

<sup>15</sup> Whiffen G.J., "Optimal Low-Thrust Orbital Transfers Around A Rotating Non-Spherical Body", Paper AAS 2004-264, AIAA/AAS Astrodynamics Specialist Conference, Maui, Hawaii, Feb. 8-12, 2004.



**Figure 11 – Feasibility Improvement from Adding a Quiet Period to the Design Process**